

# Solar Panel Experiment

By

John Hauger

Senior Project

ELECTRICAL ENGINEERING DEPARTMENT

California Polytechnic State University

San Luis Obispo

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### **Acknowledgements**

I would like to thank Dr. Shaban for giving me the opportunity to work on this project, as well as the SuPER DC Network. I would also like to thank Professor Ahlgren for his contribution of recommendations that will hopefully expand this procedure.

## **Abstract**

This senior project will focus on creating a suitable testing procedure for the provided solar panel system. The testing parameters will be based on the expected 60W output power of the system. The complete procedure will provide a thorough analysis of the power flow and overall efficiency of the system.

This senior project report will discuss the importance of this experiment in the Electrical Engineering curriculum, the system requirements and parameters tested in the design, and the provided results based on the test conditions. In addition, this report will include the complete testing procedure and recommendations for possible future additions to the testing procedure.

## I. Introduction

The purpose of these solar panels is to meet the growing demand for renewable energy resources, while expanding the available Electrical Engineering curriculum. The current coursework provided in this area relates to the conceptual understanding of how photovoltaic panels operate and their current role in society. To reinforce these concepts and show what the complete power system would include, this test procedure is based on the fundamental principles of this system in relation to power distribution. Overall, this experiment will provide students with the 'hands-on' experimentation of solar panels to encompass Cal Poly's theme of "Learn by doing."

The solar panel system involves four 15-watt panels, which are connected jointly to provide an ideal direct current (DC) output power of 60 watts. The panels are then connected to the input terminals of the battery charge controller, which is designed to provide an indication of whether the battery is charging or in the fully charged state. The output terminals of the battery charge controller are attached to the 12V solar battery terminals. The same battery terminals are also connected to the input terminals of the AC Inverter. The AC Inverter will take the supply of DC power and convert it into the more commonly used AC power.

My senior project was intended to take this system and develop an experimental procedure based on my test results. The experiment will test all of the included parts and their functionality in the system. Specifically, the power flow of the system will be examined for each segment of the system with the complete solar panel network operational.

A special project considered within this project was an analysis of the DC Network on the SuPER project. In Appendix C, this project analysis is considered based on the power losses found in a larger scale photovoltaic powered system. This is an important consideration in determining the influence of a motor on this type of system, and important ways to improve the overall efficiency of the system.

In this report, the benefits of this procedure to the Electrical Engineering curriculum will be examined in relation to the steps taken in developing it. The requirements of the system are used to complete the tested parameters needed for the lab report. With the test results for the hypothetical procedure, more precise design requirements are attuned to generate the best results with regards to the efficiency. The complete procedure and proper wiring diagrams are included.

## II. Background

In the modern world, the demand for electricity has grown at alarming rates to meet the needs of society. To meet these needs, many power companies have chosen to seek alternative sources of energy besides the fossil fuels that the current infrastructure has become dependent upon. Along this line of thinking, many have looked towards the sun to supply their energy needs, as the earth receives enough solar energy in one minute to meet the demands of one year of electricity [1]. Many other benefits to solar energy include the lack of pollution directly created by these systems and their inexpensive and viable nature. Solar energy is only restricted by weather conditions, the time of day and the manufacturing limitations of the system to supply power, where fossil fuels require a finite supply of energy and involve many complications environmentally and economically.

Based on this argument, the movement towards sustainability has become a global phenomenon, where Cal Poly San Luis Obispo State University has instilled this theme in their entire curriculum, as well as include courses specifically designed to examine renewable energy resources. Currently, these courses do not include a laboratory that tests the characteristics of solar panels to determine their functionality in a completely solar-powered system. By creating this testing procedure, the Electrical Engineering Department will be able to fulfill another theme of the university in “learning by doing”.

This experiment will provide students with a thorough analysis of a solar panel system that produces a standard 120V AC output. The four 15 watt panels form the complete 60W ideal output that powers the rest of the circuit. The primary design objective of this circuit is to charge a 12V solar battery, where the regulation of this charge is controlled by the 7 Amp



Battery Charge Controller. The charge controller provides an indication of the battery's state with a Charging and Charged lighting configuration. Ideally, when the battery is fully charged, it will provide a 12V DC output to be supplied to any load. The suggested connection to these battery terminals is the DC-to-AC Inverter, which allows the system to supply power in the standard output found in a household outlet. Each of these critical components to the solar panel system will be analyzed in depth through the experimental procedure to determine their operating characteristics and limitations.

### III. Requirements

The goal of this procedure is to develop a thorough analysis of the solar panel system to fully understand the circuit properties associated with this design. In order to create this complete analysis, each element of the circuit must be tested to determine its functionality and specifications. The best measurement to regulate the efficiency of each stage was the voltage at the output terminals. When a load is then placed across the output terminals, the power can be measured to find overall efficiency when more stages are added to the network.

First, the output of the solar panel will need to be measured to understand the stages taken to produce the output voltage of 12V needed to charge the battery. Using the open circuit voltage of the solar panel and the output of the charge controller, the exact functionality of the charge controller can be determined. If the charge controller functions as a DC-to-DC converter stepping the voltage down to the needed 12V, what output will be given if there is less than ideal sunlight. If this is not the correct operation, then how does the charge controller regulate the output voltage? Also, the lighting configuration present on the charge controller is important to consider to ensure that the 'charging light is lit when the battery is charging and the 'charged light is lit when the battery is finally fully charged.

Once the operation of the battery charge controller is confirmed, the battery can be connected to determine the complete DC network characteristics. The testing requirements needed for the battery will be based on the charging time in relation to the final voltage found across the battery terminals and the output current.

When the battery becomes fully charged, the AC Inverter can be tested to determine its complete operation. The required input voltage and measured output voltage can be used to determine the efficiency of the inverter and the overall efficiency of the entire system. The AC Inverter may have very specific requirements when loaded in regards to the available voltage and current. An important state to consider is when the solar panel is not given enough sunlight to power the AC Inverter and a given load.

#### IV. Design

The first step taken in the design process was configuring what the measurements that were going to be taken to characterize the solar panels. With the solar panel placed in the open sun with proper orientation, the open circuit characteristics of the solar panels in an ideal environment can be measured. With those results, a  $10\Omega$  resistor is inserted to determine the power characteristics supplied only by the solar panel. The operating manual provided with the system suggested an output voltage of 15V to 23.5V.

With the solar panel operation confirmed, the DC Charge Controller can be connected directly to the output terminals of the solar panel, with another  $10\Omega$  resistor connected across the output 'battery side' terminals. During this stage, the first assumption of the functionality of the DC Charge Controller was assumed to monitor the charging state of the battery, as well as provide the DC-to-DC conversion of solar panel output voltage to the necessary 12V needed to charge the battery. After testing this device though, the concluded operation of the device was to simply monitor the output voltage at the battery terminals. Based on this, the testing procedure was reconfigured to be directly connected to battery to develop a complete understanding of its functionality. With the battery connected, the charging levels and time demands can be tested until the battery reaches its fully charged state. Once it has reached the fully charged state, load testing can be done on the system to determine the efficiency of the system with the battery included.

After the operation of the system with the battery is completely charged and fully tested, the AC Inverter can be connected based on the requirements of a 12V input. The inverter can then be tested based on the expected output voltage of 120V AC. Confirming that output, the load parameters of the complete system can be tested to find the efficiency of the inverter. When testing the inverter, it should

be noted that if the inverter goes into a 'faulted' mode, where it will emit a high-pitched squeal and will not provide any output voltage. To reset the inverter, it will be necessary to turn the inverter off and back on at a suitable load value. If this does not correct the problem, the input of the inverter may also have to be reset by disconnecting and reconnecting the inverter. After my tests have been completed, an experimental procedure can be created specifically based on the limitations of the circuit elements tested in the design to further the understanding of solar panel powered system supported by the Electrical Engineering curriculum.

## V. Test Results

Placing the solar panels in direct sunlight initially, the following open circuit characteristics were measured:

**Open Voltage at junction:** 22.26V

**Expected Open Voltage Range:** 15V to 23.5V

**Equivalent Power Resistor Resistance:** 10.607 $\Omega$

To measure the load requirements of the solar panels, the power resistor was connected and measured over time to identify the complete output characteristics:

Table 1: Measured output values with the power resistor

Time	Voltage (V)	Current (A)	Power (W)
12:24pm	19.41	1.83	35.5203
12:40pm	19.28	1.817	35.0318
12:56pm	19.17	1.808	34.6594

**Average Power of Resistor:** 35.07W

**Voltage at junction:** 19.46V

**Voltage loss across leads:** 0.18V

**Power Loss across leads:** 0.327W

Some significant observations included measuring approximately 24V at the output of the solar panels, suggesting that another element in the design must be used to regulate the

output voltage at the required 12V DC output. The power output is also significantly lower than the expected 60W with an average output power of 35.07W, giving an efficiency of about 60%.

The operation of the battery charge controller was next tested. Using the tinned leads connector, the solar panel was connected to the battery charge controller through the solar panel connection leads. The voltage measured at the battery connection leads was approximately 22V, where the expected voltage output was 12V, if the charge controller also acted as DC-to-DC converter to step the voltage down. The expected lighting configuration for the charge controller was to have the 'Charging' light on for an output voltage of less than 14.2V and the 'Charged' light on for a voltage greater than or equal to 14.2V.

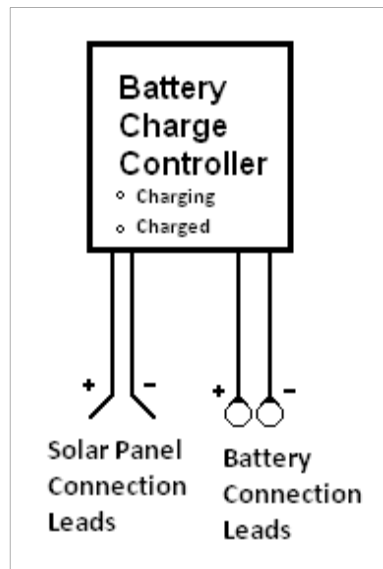


Figure 1: Solar Panel Battery Charge Controller

A  $25\Omega$  resistor was connected across the Battery Connection Leads, where the measured output voltage was about 0.2V. The measured current was negligible. Both the charging and charged lights were on during this test. Considering this data, it is concluded that charge controller must sense the necessary output voltage that it needs to supply. Because the resistor is not providing this reference, the supplied voltage and current are relatively small.

To confirm the charge controller's functionality, a solar battery was connected to the battery connection leads. Before the battery was connected, the voltage across the terminals was measured to be 8.84V. The initial charging voltage across the battery connection leads was approximately 22V and gradually decreasing as the battery was being charged. When the battery was fully charged, the final voltage was approximately 14.2V and the final current was 1.4A. The charging and charged lights on the charge controller were flickering on and off during this step. Contrary to the predicted operation of the charge controller as a DC-to-DC converter



and a battery charge regulator, the voltage data suggests that the output changes in response to the characteristics of the load. When the input does not supply enough power to handle the load, the output voltage drops along with the output current.

After the battery was fully charged, the AC Inverter was connected across the battery terminals with the negative lead connection followed by the positive lead connection. The inverter was then turned on, with the green 'power' light being lit.

Turning off the AC Inverter, a transformer was connected to adjust the output AC voltage to a desired range, so as to not overload the output current limitations. A decade power resistor was then connected at the output of the transformer through a watt-meter to measure the output voltage current and power. The transformer is initially adjusted to supply no voltage to the resistor. With the inverter turned on, the open circuit characteristics of the AC Inverter were used to confirm the correct operation with the transformer:

**AC Inverter Output Open Circuit Voltage = 118.5Vrms**

**AC Inverter Input DC Voltage = 12.5V**

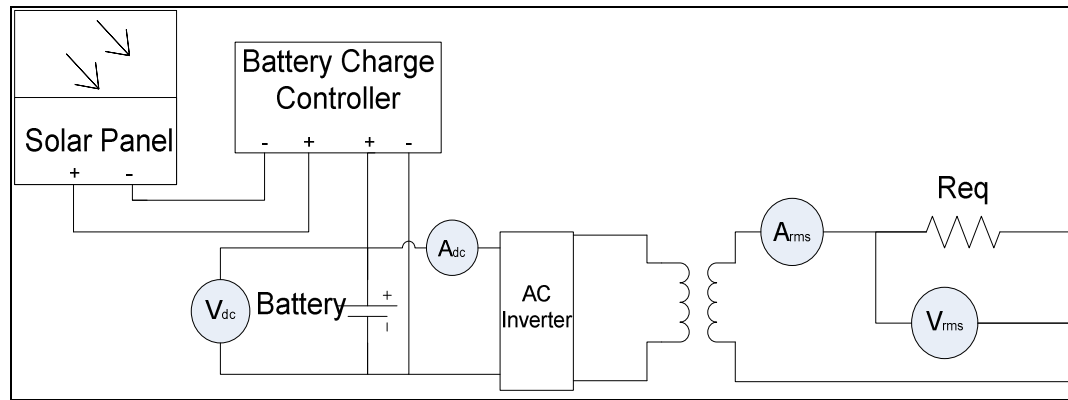


Figure 2: AC Inverter Circuit Diagram

After the functionality of the transformer was confirmed, the power resistor was adjusted to determine the load characteristics of the system. By varying the load from a relatively low to a high resistance, the response of the system can be mapped to determine the overall power characteristics of the system.

Table 2: AC Inverter Test Results

$R_{eq}(\Omega)$	$V_{dc}(V)$	$I_{dc}(A)$	$P_{in}(W)$	$V_{rms}(V)$	$I_{rms}(A)$	$P_{out}(W)$	Efficiency
400	12.64	2.71	34.25	100.6	0.257	25	73%
500	12.94	2.3	29.76	103.4	0.213	21	71%
600	13.12	2.02	26.50	104.9	0.182	18	68%
700	13.35	1.82	24.29	105.9	0.159	16	66%
800	13.56	1.67	22.64	107	0.142	14	62%
1000	13.85	1.45	20.08	108.9	0.118	12	60%
1100	13.45	1.36	18.29	106.5	0.106	10	55%
1200	13.55	1.29	17.47	107.6	0.098	9	51%
1500	13.73	1.12	15.37	108.9	0.082	8	52%
2000	13.79	0.95	13.10	109.5	0.064	6	46%
2500	13.82	0.86	11.88	109.7	0.054	5	42%
3000	13.82	0.8	11.05	109.8	0.047	4	36%

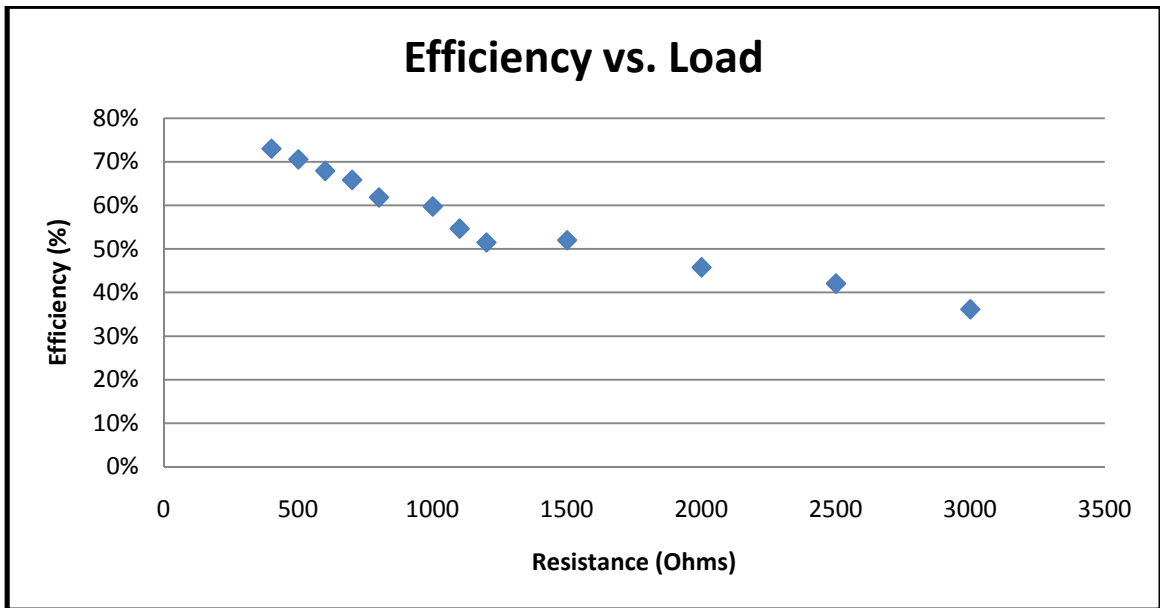


Figure 3: Efficiency of the system at various loads

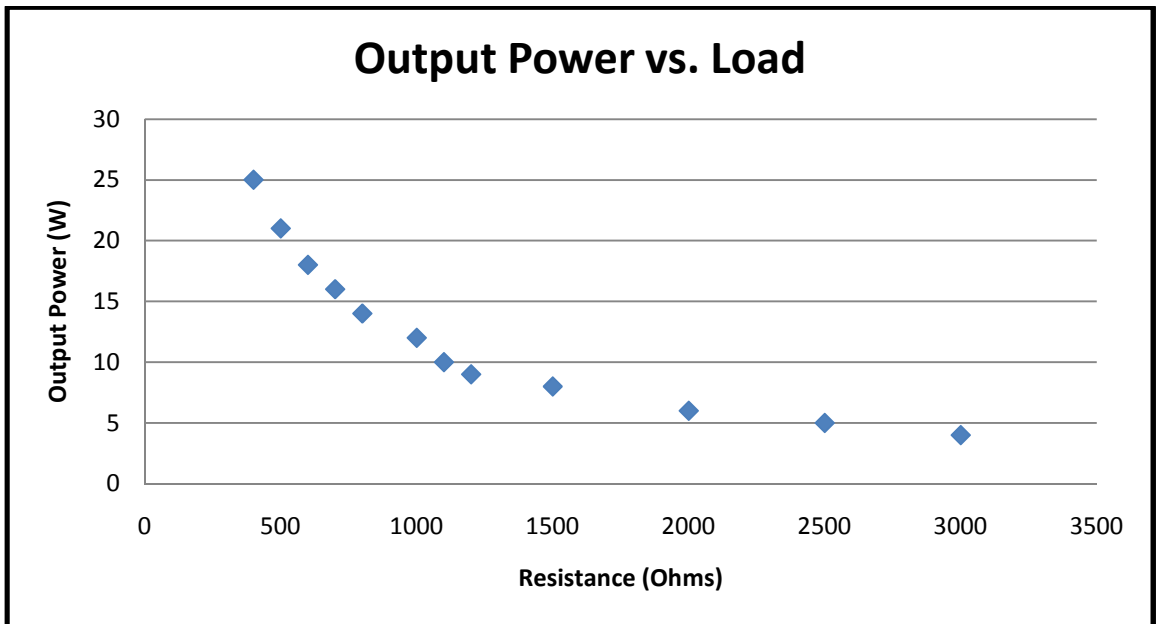


Figure 4: Output Power of the system at various loads

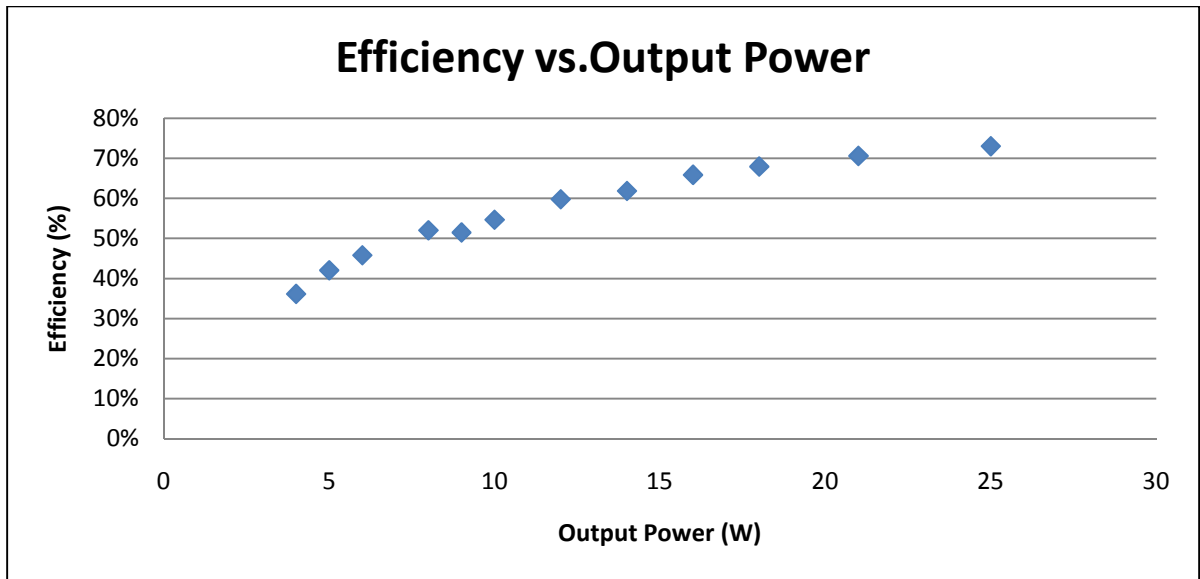


Figure 5: Efficiency of the system based on the available Output Power of the system

This test confirms the functionality of the AC Inverter in producing the required AC output voltage. As the load increases, the efficiency and output power of the system go down, as expected. The limitations to the inverter are identified to be based on the load requirements for the system. In the final procedure, the ideal range of loads to test will be less than  $1k\Omega$ .

## **VI. Conclusion and Recommendations**

The solar panel procedure is outlined in the same basic manner as the testing procedures conducted on the solar panels to determine their proper operation. The desired measurements taken in the experiment directly relate to the objectives of the current Renewable Energy Resources curriculum of “The objective of this course is to stimulate the search for creative solutions to one of the central problems of the 21<sup>st</sup> century: how to provide California and the world with electric power in a sustainable manner [2].” For the purposes of the Electrical Engineering curriculum, this procedure will provide a complete power analysis of a solar powered electrical system.

Several additions to expand this experiment were suggested by Professor Ahlgren to provide more insight into the physical functionality of the system. A module for the system could be created to test the system under certain conditions. The module would include several screen filters to see what impact a lower level of light will have on the system. Also, thermal couples can be attached to each side of the solar panel to measure the temperatures in front of or behind the solar panel, as it has been observed that there is a strong trend between temperature and output efficiency. A pyranometer could also be added to the module to measure the light intensity as these tests are conducted to relate the amount of light being input to the solar panel characteristics. A more advanced version of this module can include a mechanism to control the orientation and angle of the solar panel to ensure the maximum amount of light input. Another suggestion was to open the DC charge controller and AC Inverter to determine the exact functionality and design specifications chosen for this system. If this lab was branched out further into a power analysis class, then this system could be connected to

the grid in hope of supplying voltage back to the utility. It should also be noted for future experimentation that the AC Inverter does not react well with small loads, where the current exceeds the ratings given by the circuit. The best way to approach this issue is to have a load with a large resistance and to use the Auto-Transformer to start at a small output voltage and to gradually increase it to the final terminal voltage of around 110V.

## VII. Bibliography

[1] AEI. "Renewable Energy, Solar Energy." *Alternative Energy - Wind, Solar, Hydro and other alt energy sources*. Web. 20 Nov. 2009. <<http://www.altenergy.org/renewables/solar.html>>.

[2] Ahlgren, Bill. Course Information – EE 420, Sustainable Electric Power. Fall 2009.

[3] Harris, James G. White Paper for Sustainable Power for Electrical Resources-

SuPER. July 15, 2005.

<[http://www.ee.calpoly.edu/~jharris/research/super\\_project/white\\_paper\\_suspender.pdf](http://www.ee.calpoly.edu/~jharris/research/super_project/white_paper_suspender.pdf)>

[4] Witts, Joseph. SuPER Cart DC Motor Model and Ultra-Capacitor Addition. March 18, 2008.

< [http://courseware.ee.calpoly.edu/~jharris/research/super\\_project/jw\\_spring08\\_report.pdf](http://courseware.ee.calpoly.edu/~jharris/research/super_project/jw_spring08_report.pdf)>

[5] Cao, Jennifer. SuPER Project Wiring and System Protection. December 2006.

< [http://courseware.ee.calpoly.edu/~jharris/research/super\\_project/jc\\_sp.pdf](http://courseware.ee.calpoly.edu/~jharris/research/super_project/jc_sp.pdf)>

## Appendix A: Time Schedule Allocation

Table 3: Estimated Time Schedule

Estimated Time	
Task	Hours
Outline testing procedure for solar panel	15.0
Solar Panel Testing	10.0
DC Charge Controller Testing	12.0
Battery Testing	10.0
AC Inverter Testing	15.0
Data Organization	5.0
Total	67.0

Table 4: Actual Time Allocated

Time Used	
Task	Hours
Outline testing procedure for solar panel	15.0
Solar Panel Testing	9.0
DC Charge Controller Testing	6.0
Battery Testing	10.0
AC Inverter Testing	22.0
Data Organization	6.0
Total	68.0

Though the estimated amount of time and actual amount were very close, this is primarily due to the simplicity of the DC Charge Controller and various difficulties met in get the AC Inverter to operate correctly.



## **Appendix B: Solar Panel Experiment Procedure**

### **Experiment #: Solar Panel Characteristics**

#### **Introduction**

This experiment will deal with the properties of solar panels and the output power generated as a result of specific circuit devices. In testing how the solar panels react to certain circuit elements, a better model for those parts and solar generation on a larger scale can be made. The battery will provide the experiment with the necessary DC source to control the input of the AC Inverter in generating an ideal output.

#### **Equipment:**

7 Amp DC Charge Controller

200W Modified Sine Wave DC to AC Power Inverter

4-panel Photovoltaic Panel Set

10 Banana-to-Banana leads

2 Meter Lead Sets

1 Bag of Short leads

8 Alligator Clips

1 Phase Wattmeter

2 Multimeters

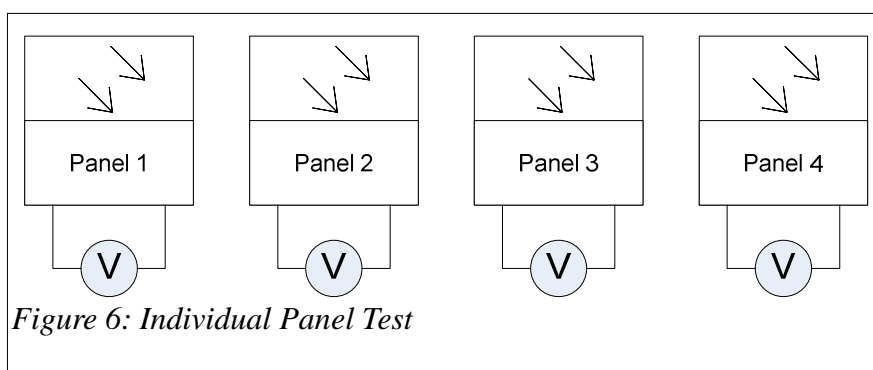
Auto-Transformer

## Procedure:

### A. Solar Panel

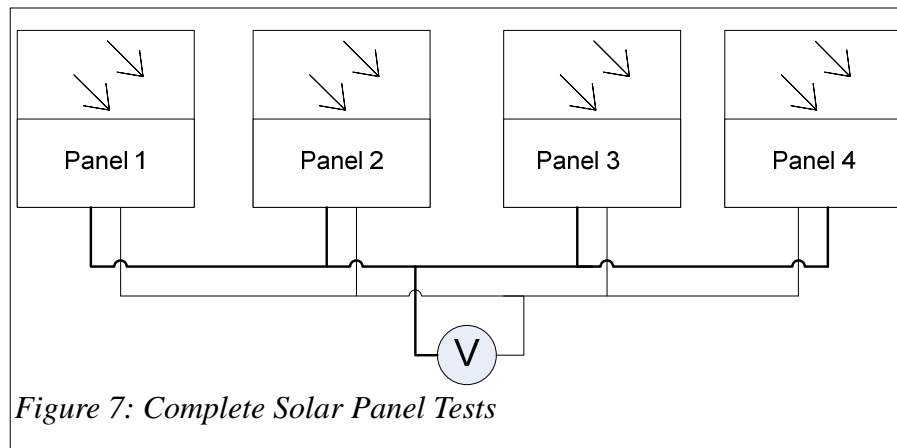
1. Assemble and place panels in direct sunlight, see Figure 1.
2. Measure and record the voltage of each individual panel:

Panel	1	2	3	4
Voltage				



3. Connect panels together at junction and measure output voltage of the combined panels, see Figure 2:

Total Voltage =

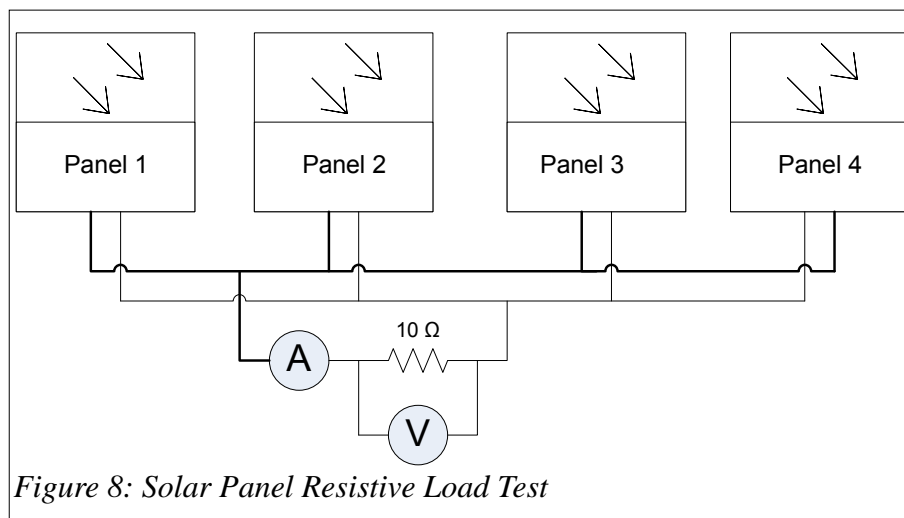


4. Connect  $10\Omega$  power resistor in parallel with the solar panel and measure the output voltage and current, see Figure 3. Calculate the power.

Voltage =

Current =

Power =



5. Connect two and three  $10\Omega$  power resistors in parallel with the solar panel and measure the output voltage and current. Calculate the power.

Resistors	Resistance	Voltage	Current	Power
2				
3				

### B. Charge Controller

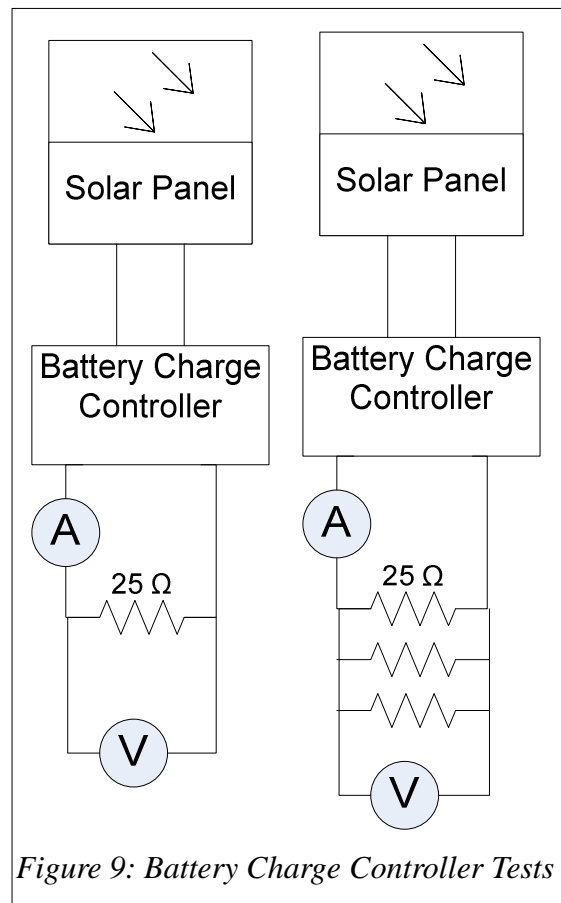
1. Connect the tinned wire connection to the input leads of charge controller. Plug the input into the output junction of the solar panels.
2. Connect the  $25\Omega$  power resistor across the output leads of the charge controller. Measure the voltage and current across the resistor, see Figure 4. Record the lighting configuration observed on the charge controller.

Voltage =

Current =

3. Connect two and three  $25\Omega$  power resistors in parallel with the output leads of the charge controller, see Figure 4. Measure the voltage and current across the resistor. Record the lighting configuration observed on the charge controller.

Resistors	Resistance	Voltage	Current
2			
3			



4. Determine the efficiency of the Charge Controller.

### C. Battery Charging

1. Measure output voltage of the battery before connecting it into the system

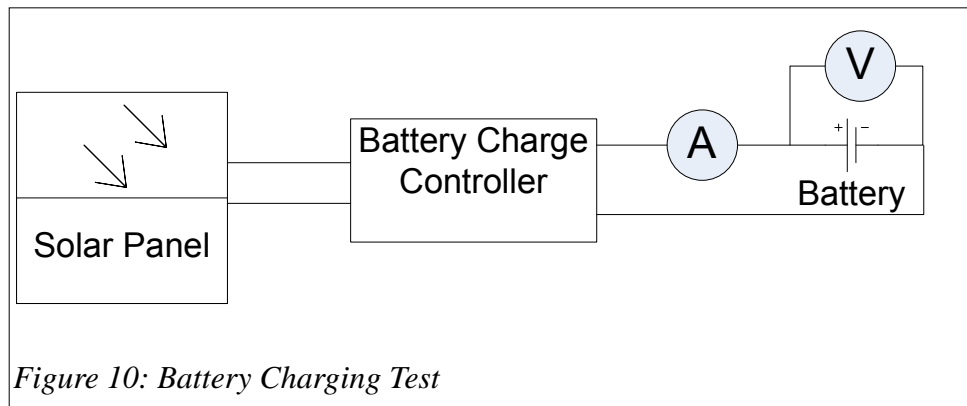
Voltage =

2. Replace the  $25\Omega$  with the battery and measure voltage and current until a final voltage of around 14.2V and a small current is output, see Figure 5. (Caution: When connecting the solar panel to the battery, be very careful not to short the leads across the battery. Keep the connecting leads as far apart as possible.) Record the voltage and current at the start, after 15 and 30 minutes of charging and at the final voltage.

Initial Voltage =

Initial Current =

Final Voltage =



3. Create a plot to show the change in output voltage over time.

#### D. AC Inverter

1. With the battery still connected, attach the AC inverter input leads to the appropriate battery terminals, see Figure 6.
2. Measure the AC inverter output voltage and input DC voltage.

AC Voltage =

Input DC Voltage =

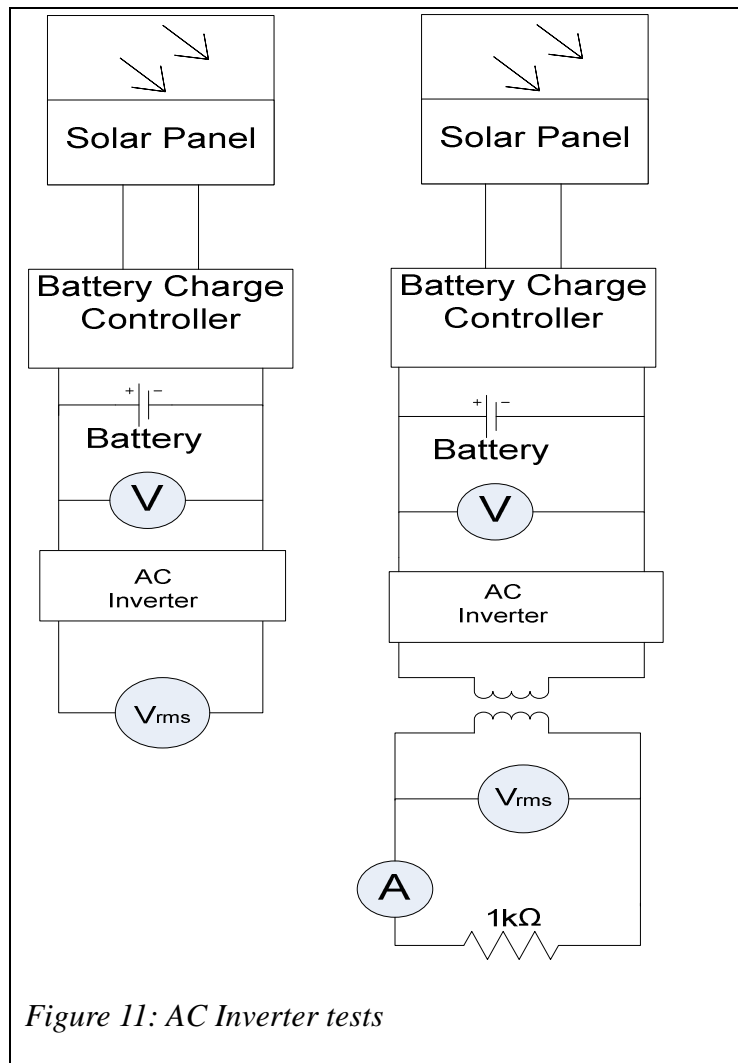
3. Attach the transformer to the output of the AC Inverter. Adjust the transformer to initially output no voltage. Attach a decade power resistor to the output of the transformer, see Figure 6. Adjust the transformer to output the maximum voltage to match with the output current limitations of the inverter. Adjust the decade power resistor to 1kΩ. Measure the output AC voltage of the transformer, output AC current and input DC voltage on the inverter. Compute the input power, output power and efficiency.

RMS Voltage across Resistor =

RMS Current =

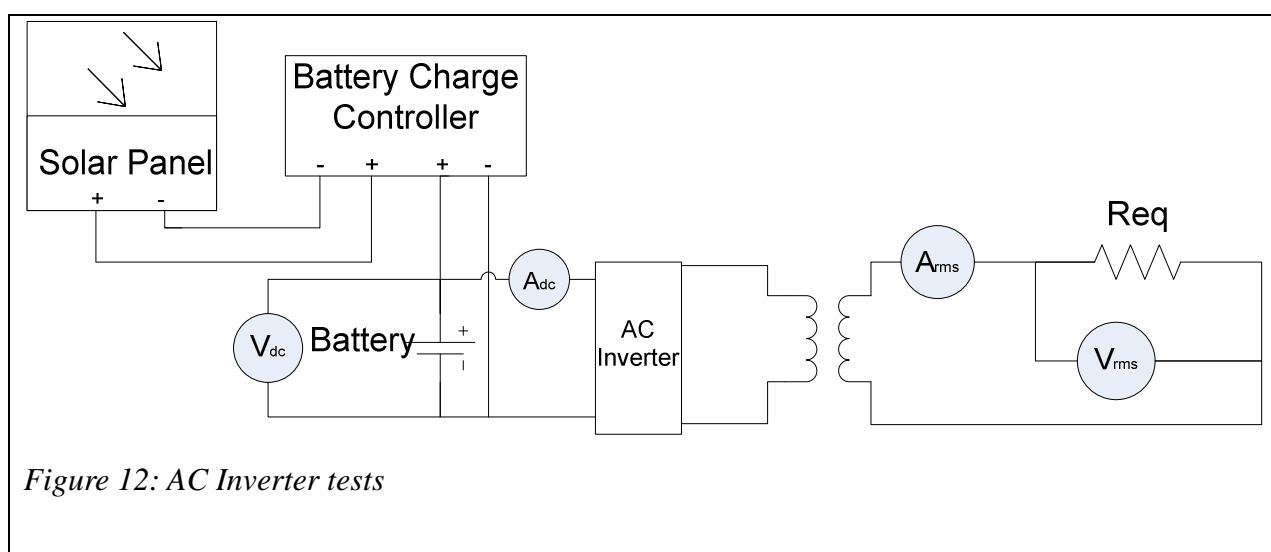
Input DC Voltage =

Input DC Current =



4. Repeat the step 3 with a resistance from  $400\Omega$  to  $800\Omega$  across the output of the transformer in steps of  $100\Omega$ , see Figure 7. Measure the output AC voltage, output AC current, input DC current and input DC voltage. Determine the input power, output power and efficiency.

Equivalent Resistance	AC Voltage	AC Current	DC Voltage	DC Current
400 $\Omega$				
500 $\Omega$				
600 $\Omega$				
700 $\Omega$				
800 $\Omega$				



- Determine the efficiency of the AC Inverter.



## **Appendix C: SuPER Project DC Network**

### **I. Introduction**

The SuPER Project focuses on providing a renewable energy resource for implementation in an area isolated from a power grid. The source of the power is a 150W solar panel, making the ideal location for this system have significant solar radiation, such as many third world countries. The overall plan is to provide low-cost, sustainable power for individual households with a 20-year life cycle [3]. Because of the growing demand for an electrical resource in society, the need for these types of systems will increase, thus making the improvement of power losses critical to the future of the SuPER Project.

The SuPER project uses the solar panel to provide a DC source to the loads and battery. The loads include a refrigerator, a TV, lights, a laptop, and a DC motor. The laptop consumes a 15 W of power currently, but will be replaced with an FPGA board; which will only consumes milliwatts of power. Otherwise, the DC motor will consume a significant percentage of the available output power. The Dayton 6MK98 12V ¼ hp motor is also expected to be the main source of power losses present in the system, due to the significant amount of electrical power needed to handle greater mechanical loads. The ultra-capacitor will aid in providing power initially to the DC motor, so its functionality and power losses will also be considered in the analysis of the system.

In this report, my senior project will be outlined based on the background of the SuPER system, the requirements needed to maintain the system in the most efficient manner, the design proposed to improve power losses, the tests involved in the system to confirm the

significant sources of power loss, and finally, how these improvements will benefit the future system within the scope of the project.

## II. Background

The SuPER project is designed to supply DC power to several loads and charge a battery. The output voltage of the solar panel is 40V, which is stepped down to 12V with a DC-to-DC Converter. The main switch board controls the distribution of this voltage with the combiner box protecting the current levels supplied to the loads, as seen in Figure 1. Figure 1 is based on Joseph Witt's wiring diagram, where the gauge of the wire is related to the thickness of the connection. The current ratings of the associated gauges have also been included for the related connections that will be inspected. The loads included are based on the expected needs of individuals in a third world nation. A DC motor is included in the loads, assuming that this system will be used in agricultural irrigation or water pumping. Because of the provided DC motor connection, the unnecessarily large cable and current drawn by the load combine to contribute to the power losses in the system. The battery is also charged by the solar panel and regulated by the main switch board. When the motor is turned on, an ultra-capacitor is used to help supply the initial power needed to get the motor running. The ultra-capacitor is regulated by a separate capacitor switch board that also helps control the battery voltage. These components make up the significant sources of power consumption within the SuPER system.

In a network powered by a DC supply, losses throughout the system can significantly impair the output power of the system. With the SuPER project being supplied by a solar panel and battery, a finite amount of energy is available and heavily reliant on the current weather conditions and the time of day. To improve the overall efficiency of the system, the output power will need to be increased by reducing the power losses found in the system. The current wiring design is based on conservative estimates, where the amount of current passing through

the wire is significantly less than the current ratings of the wires. By matching the current ratings of the connections closely to their maximum expected current, unnecessary power losses in the system can be minimized.

The goal of my senior project was to analyze the SuPER wiring design to locate where improvements could be made in increasing the efficiency of the system. Based on the preset provided loads and their expected power consumption, current ratings for their connections can be based on those values and the given 12V output. Ideally, the most power consumption will occur when the motor is operational. Following the path of power during this phase will provide the information needed to determine the maximum power losses possible in the system.

Using a motor model based on simple circuit elements, power analysis of the system can be simplified to find the ideal motor results through simulation. In the simulation and analysis, the significant sources for power loss in the wiring system can be identified. A complete model of network and the motor will provide the basic foundation for this step. Following the results from the simulation, the actual system can be tested to quantify where some problem areas exist. With this analysis, the efficiency of the system can be improved to adjust certain aspects of the DC network in regards to the length of the wiring diagram.

### III. Requirements

The primary requirements of the SuPER system, in regards to the power distribution of the system, are to maximize the output power while maintaining the efficiency of the system. Following the flow of power from the solar panel to the motor, the specifications for the maximum amount of power consumption can be determined. Each wiring connection must maintain the proper rating to allow the maximum current enter and exit each element needed to supply power to the motor.

Table 3: SuPER System Currents

Component	Solar Panel	DC-DC Converter	DC Motor	Ultra Capacitor	Lights	TV	Laptop	Refrigerator	Battery
Current (A)	4-8	15	20	10	1.25	0.67	3.5	0.69	30

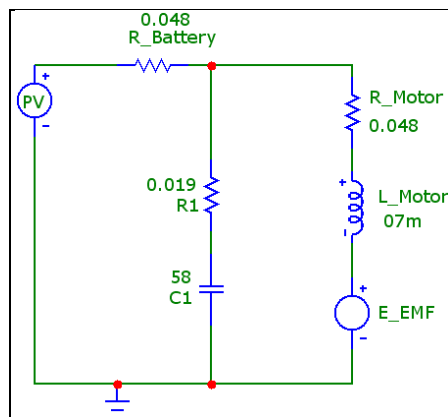
When simulating the results for the motor, a proper model and suitable results in the tested range of torque values will be needed to make an accurate comparison with the test results. The maximum torque can be found based on the speed ratings of the motor (1800 rpm) and the relation of the power to the torque of the motor:

$$\begin{aligned}
 P[W] &= 1.18 \times 10^{-2} * T[lb-in] * n[rpm] \\
 \frac{1}{4}(746) &= 1.18 \times 10^{-2} * T * 1800 \\
 T &= 9.1624[lb-in]
 \end{aligned}$$

To find the complete contribution of the motor cable to the power losses, the motor will be tested when disconnected from the SuPER system. Because this is the test scenario, the simulation will also be analyzed under these conditions.

#### IV. Design

To create an adequate simulation of the system, a model of the motor had to be found that included the important power specifications of a permanent magnetic DC motor. From Joseph Witts analysis and simulation of the DC motor and Ultra-capacitor, a simplified model of the motor from an electrical perspective was obtained. Based on Joseph Witts' model of a DC motor, a resistive and inductive element is connected in series with the back EMF source to simulate the electrical response. With the provided specifications from the motor included into the set conditions from the remainder of the system, the following simulation diagram of the power throughout the system was generated:



*Figure 1: Circuit analysis of motor simulation*

To ensure the accuracy of the tested model with the given parameters from Joseph Witts' specifications, the circuit was compared to Jennifer Cao's test results on the motor.

#### **Motor Specifications [4]:**

Motor Resistance:  $0.048\Omega$  @  $25^\circ\text{C}$

Back EMF Constant:  $6.64\text{ V/kRPM}$

Motor Torque Constant: 0.56 lbs-in/A

Rotational Inertia: 3.12 lb\*in<sup>2</sup>

Armature Inductance: 0.33mH

Stall Torque: 99 in-lbs @ 179A

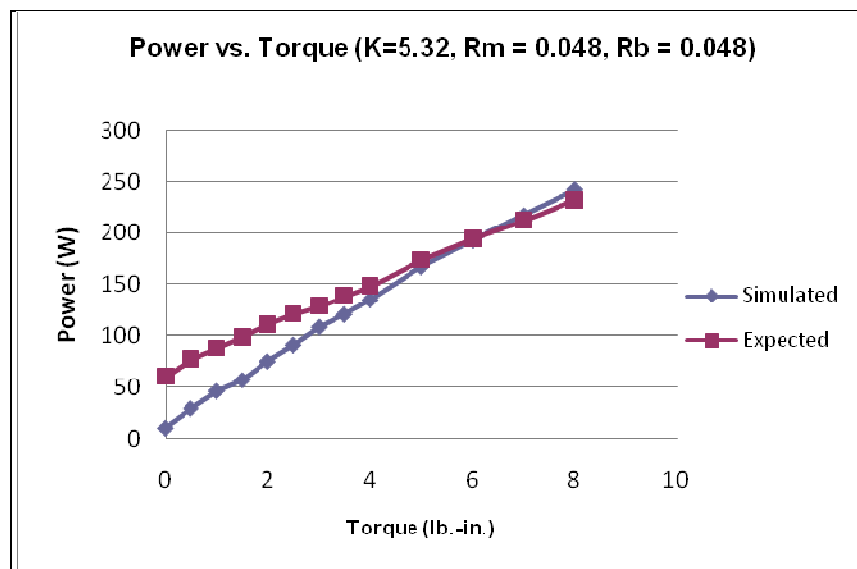
Table 2: Jennifer Cao's test results on motor[5]

Torque [lb-in]	Speed [rpm]	Voltage [V]	Current [A]	Power [W]	Efficiency [%]
0	1840	12.26	5.1	62.526	0.000
0.5	1734	11.74	6.6	77.484	13.226
1	1670	11.41	7.2	82.152	24.028
1.5	1620	11.16	8.1	90.396	31.774
2	1588	11.08	9	99.72	37.646
2.5	1500	10.64	9.9	105.336	42.080
3	1470	10.6	10.8	114.48	45.533
3.5	1460	10.6	11.7	124.02	48.702
4	1425	10.4	12.6	131.04	51.415
5	1270	9.7	15	145.5	51.586
6	1140	8.9	16.2	144.18	56.075
7	1060	8.7	18	156.6	56.005
8	939	8.14	19.8	161.172	55.091

The most significant difference between these two sets of data was the values of the current, where the K parameter was adjusted to generate better results. The value of K was reduced to increase the current and power output, using the equation  $E = K \cdot \phi \cdot \omega$  as a basis for this assumed response.

By adjusting K from the given 6.64 to around 5.32, the trend curve matched the expected current and power results around 1800 rpm (4 lb-in. torque) with the nearly the same voltage for every speed measured. To further improve the slope of the curve for the higher range of speeds, the resistance of the motor was adjusted slightly. This model produced power and current values that were within the range of the ideal operating region for the motor. With

this information on the predicted operation of the motor under these constraints, the losses in the wiring of the current system can be better identified to maximize the efficiency of that system. The following power consumption results were found as a result of the varying torque values:



*Figure 2: Circuit analysis results for the motor model*

Using this complete model, a more detailed examination of the surrounding wiring system can be done. As the current through the system changes for each torque value, the voltage found at the terminals of the motor remain relatively constant. Before doing a thorough inspection of the complete system, the diagram of the wiring is further adjusted to provide more information relative to the power consumption. Referring to the previous schematics done, a combination of wire gauges and proper connections with the included ampacity values allow for an optimal diagram for power analysis. With this complete model and measurements



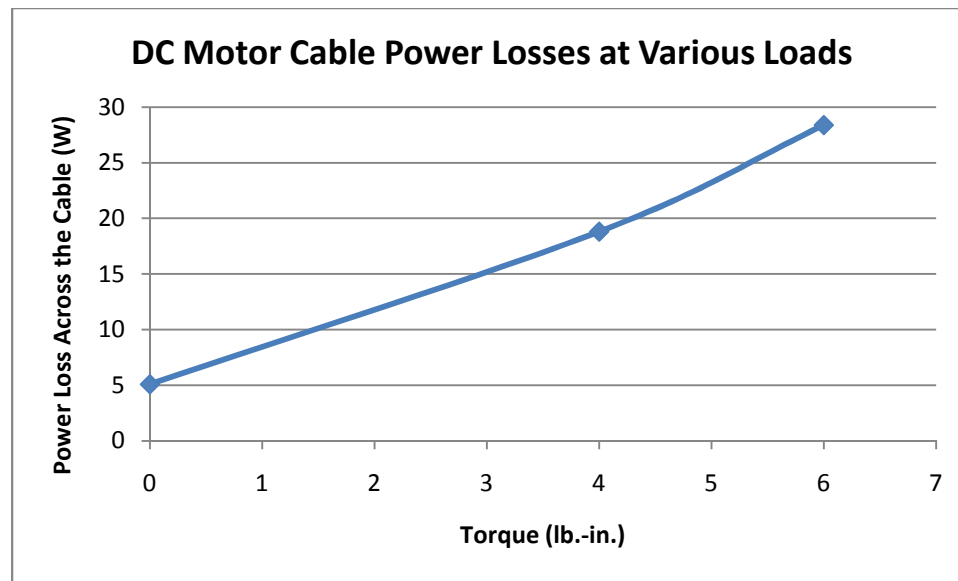
of the power losses related to the wiring diagram, areas for improvement identified will be better to organize for the power losses.

## V. Test Results

With the simulation results as a basis for what the expected results will be, tests on the motor with the included cable can be analyzed to find the power losses due to the cable. The voltage measurements will be taken at the terminals of the motor and at the connection of the cable to the power source. By measuring the voltage at these two points, the voltage difference can be used to calculate the power lost across the cable and the equivalent resistance. Then with the given system, an ideal cable length and wire gauge can be suggested to better fit the design.

Table 3 : DC Motor Cable Testing

Speed (rpm)	Torque (lb.-in.)	Voltage at Motor Terminals (V)	Voltage at Input (V)	Current (A)	Cable Resistance ( $\Omega$ )
1736	0.0	11.61	12.37	6.7	0.113
1157	4.0	8.36	9.72	13.83	0.0983
900	6.0	7.07	8.74	17.0	0.0982



*Figure 3 : DC Motor cable power losses at various torque loads*

Based on these results, the cable will consume the most power losses when the motor is at full load, as the largest amount of current is drawn. Because of this large current, the connecting cable power consumption drastically increases to up to 28W. But because this is only the worst case scenario for the operation of the motor, the typical characteristics will operate closer to the 4 lb.-in. measurement. Due to this significant power loss found in the circuit, the length of this cable should be altered to reduce this significant power loss to only meet the minimum connection on the SuPER system.

## **VI. Conclusion and Recommendations**

The DC network was analyzed to determine the power losses contributed by the motor's operation. By identifying the parameters associated with the full load scenario, the largest amount of power flowing through the circuit can be examined. Overall, the resistances found in the system are too small to make a dramatic impact on the power losses found in the system.

For future designs of the SuPER project, the wiring gauges can be more closely matched to the expected maximum currents, while still including the regulations designated by the NEC Handbook. The DC Motor connections can also be altered to provide solid connection to the system, but not at an excessive length. Ideally, the length of the cable can be reduced to 2 ft from the original 6 ft. This would be the best fit in the current system, but depending on the water system it would be connected to; this length or longer may be necessary to be closest to the water source. If the user's motor needs for the system are met without this extraordinary length, then power losses can be significantly reduced by using a shorter cable. This will also benefit the overall efficiency of the system, in regards to when the motor is operating.

## Time Schedule Allocation

Table 3: Estimated Time Schedule

Estimated Time	
Task	Hours
Simulate overall circuit in Pspice	12
Take experimental data on system to compare to simulation	27
Analyzed results of each to identify problem areas that may cause inefficiency	12
Develop solutions to be implemented into an altered design and attempt to simulate	15
Organize data comparing the two design scenarios	20

Table 4: Actual Time Allocated

Time Used	
Task	Hours
DC Motor Model	15.0
Simulation of DC Motor Model and Correction	15.0
Analyze complete system with provided simulation data	5.0
Take experimental data related to motor operation	10.0
Find total power losses attributed to the system running at full-load	5.0
Compare given data on the system to find the total power losses for a whole day	5.0
Provide altered schematic suggestions to improve on current design	5.0